A Site-Specific Center Pivot Irrigation System for Highly-Variable Coastal Plain Soils

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ABSTRACT

The Coastal Plains Soil, Water, and Plant Research Center has been monitoring spatial yield in a test field since 1985, using a conventional corn-wheat-soybean rotation most of that time. Observations of variation in soil and crop response that correlate with yield variation suggest that crop water relations may be the key feature that causes spatial variability in yield for the Southeastern Coastal Plain. Experience with mechanistic modeling indicates that for normal weather years, the final yield is particularly sensitive to variations in soil water, presumably because the surface soil is sandy and rooting volume is limited. These conclusions, plus difficulties encountered in scheduling irrigation under a center pivot on typically variable soils, led the USDA-ARS to design and build a site-specific center pivot capable of differentially irrigating 100-m^2 areas. A 3-tower commercial center pivot was modified by adding 39 9.2-m manifolds in 13 sections, 3 to a section. The manifolds and nozzles were sized 1x, 2x, and 4x, so that octal combinations would provide up to 7x the minimum application depth for a given outer tower speed. At 50% speed, the application depths are 0 to 12.5 mm in 1.8-mm increments. A programmable controller was attached near the pivot end of the boom, so that it was proximal to but avoided the pivot control panel when the system rotated. The individual manifolds were controlled by a program residing in the programmable controller, which obtained pivot position and other information via radio modem link with the pivot control panel. Water and nitrogen application has been accomplished using this system on a replicated field experiment. Experience gained during this phase will guide modification of a similar pivot for site-specific water, nutrient, and pesticide management on a typically variable Coastal Plain field.

INTRODUCTION

The southeastern US Coastal Plain is comprised of nearly level, sandy surface soils overlying a sandy clay subsoil (Pitts, 1974; USDA-SCS, 1986). The terrain is marked by numerous Carolina Bays, which are shallow (<3 m) depressions of varying size and indeterminate origin. Surface texture within the depressions is generally finer than that outside, with the deeper depressions tending toward clays, and the shallower ones, loams. The bulk of the soils outside the bays is sandy loam or loamy sand, with extensive inclusions of sands. Much of the Coastal Plain also has an eluviated E horizon of similar texture to the A, but with essentially no organic matter, and increased density (1.7 to 1.8 g cm^{-3} being common). Thickness of the A horizon and both existence and thickness of the E horizon are important distinguishing characteristics of the soils for a given area. The sandy soils and root-restricting eluviated horizons combine to make nonirrigated crop production a challenge in the area. Management practices to increase rooting depth include subsoiling to a depth of about 0.4 m beneath the crop row.

Climate in the area is warm, humid, and frequently cloudy. Average annual rain for Florence, SC, is 1100 mm/yr. Most summertime rain occurs in thunderstorms, such that June, July, and August are the months with highest monthly total rain, from 100 to 150 mm/month. However, each month during the growing season has 110-yr record low totals in the 20-mm range, and record high totals in the 250-mm range. Such variability in rainfall, coupled with the poor water relations described above, means that yield-reducing drought stress is common in an area one would otherwise assume had plentiful rain. Sheridan et al. (1979) reported that 22-d droughts during the growing season occur, at 50% probability, every other year. Such drought dramatically reduces crop growth and yield.

Observations of spatial patterns in crop growth, particularly during periods of drought, suggest water management may be the key for managing soil variability in the Coastal Plain (Karlen et al. 1990; Sadler et al., 1995a; 1995b). Similarity of yield patterns during drought and non-drought years (though with differing means) supports this assumption. Further support comes indirectly from the apparent non-correlation between yield and fertility patterns. Local experience in scheduling irrigation for a center pivot sited on variable soils had set the stage for the problems one would encounter when attempting to spatially manage soil water (Camp et al., 1988).

Consequently, in 1991, an irrigation system design team drew up specifications for a computer-controlled, variable-rate center pivot (see Camp & Sadler, 1994). Two commercial machines were acquired (description below), and modifications were made to achieve this objective. The machine was first used during the 1995 season, and demonstrated under the controlled conditions of a replicated experiment on a reasonably uniform field. The second machine, which will be modified during 1996 based on experiences with the first, will represent the final stage of the process -- that of variable-rate management of water, fertility, and pesticides on a highly variable Coastal Plain soil.

Concurrent with the above process, three other research groups have been working toward similar goals. Lyle (personal communication, 1992) described a multiple-orifice emitter design that could be individually switched to provide a series of step-wise incremental flow rates. This was part of the Low-Energy Precision Application (LEPA) system. Duke et al. (1992) and Fraisse et al (1992) described an alternative time-slice approach in which variable rates were achieved by switching sprinklers on and off for varying proportions of a base time period, usually 1 min. The advantages of this design are that a continuous range of application rates can be obtained using a single nozzle, where the others' systems require additional nozzles, manifolds, and switches to achieve additional increments of rate. The disadvantage is that the on/off sprinkler may be either in phase or out of phase with the start-stop motion of the irrigation tower, impressing additional variability in application depth. This disadvantage is minimized when the wetted radius is larger, the alignment of the irrigation machine is controlled very closely, and the base time period of the sprinkler is small relative to the duration of tower stoppage. Stark et al. (1993) used a similar concept with a patented (McCann & Stark, 1993) control system for a variable-rate linear-move system, in which individual conventional sprinklers were controlled by computer. Three sprinkler sizes (1/4, 1/4, ½ of full flow) provided 1/4, ½, 3/4, and full irrigation. This system was installed on a field-scale center pivot, and uniformity of application was reported. Further developments on a linear move system were reported by King et al. (1995).

The objective of this presentation is to describe the variable-rate center pivot machine developed at Florence, and to illustrate its capabilities to the precision agriculture audience.

MATERIALS AND METHODS

The design specifications of the center pivot irrigation machine were to achieve practical variable-rate control on control elements of approximately 100 m^2 area. The unit needed to be able, at normal operating speeds (usually 50% duty cycle of the outer tower), to apply sufficient water to replace an average daily potential ET. For practical reasons, 8 discrete increments of the potential ET were considered as a minimum working approximation of true variable-rate irrigation. Control of the application rates was to have been achieved using computerized maps, so that algorithms, yet to be developed, could be employed to choose application depths based on historical yields, soil maps, or on-board sensors. Further, the variable-rate modifications were to be implemented on commercially-available systems. An overview of the concept is described in Camp and Sadler (1994).

The hardware for this system is described in Camp et al. (1996), and will be briefly summarized here. Two small, 3-tower, 137-m commercial center pivots were purchased in 1993 (Valmont Irrigation, Inc, Valley, NE). In anticipation of increased load, a heavier truss design was requested. Otherwise, the unit was conventional in both design and control. A set of overhead sprinklers and a set of LEPA quad sprinkler heads on drop tubes were installed on both machines, to provide immediate ability to irrigate, albeit uniformly.

The design and modification of the manifolds and sprinklers for the first commercial pivot were done in cooperation with The University of Georgia Coastal Plain Experiment Station, Tifton, GA. More details of the hydraulic design can be found in Omary et al. (1996). In brief, the length of the truss was logically segmented into 13 sections 9.1 m (30 ft) long (see Fig. 1). Each of these sections had 3 parallel, 9.1-m manifolds, each with 6 industrial spray nozzles on 1.5-m spacing. Water was supplied to each set of 3 manifolds directly from the boom via 5-cm (2 in) ports, drop pipes, a tee, and hoses. Each individual manifold had a solenoid valve, pressure regulator, low-pressure drain, and air entry port. The 3 manifolds and their nozzles were sized to provide 1x, 2x, and 4x of a base depth at the position of the section, which meant that all actual flow rates were larger at the outer end to account for the greater area subtended per unit angle traveled. Octal combinations of the 3 manifolds provided 0x, 1x, 2x,...7x the base depth. The 7x depth was set to 12.5 mm (0.5 in) at 50% duty cycle on the outer tower. The small size of the unit, 120 m, meant that a full circle could be irrigated in less than 4 hr at 100% duty cycle, so that a 17% setting could still complete the circle in less than 24 hr.

All solenoids were controlled using a programmable logic controller (PLC: GE-Fanuc model 90-30, Charlottesville, VA[1]) mounted on the mobile unit, about 5 m from the pivot point, far enough to clear the tripod and control box. The PLC had an on-board 80386 PC with hard drive, floppy drive, serial ports, and peripheral connectors. Software was written in Visual Basic (Microsoft Corp., Redmond, WA) to convert a map of control values to on-off settings in the directly-addressable solenoid control registers of the PLC. In order to determine location from the C:A:M:S (Valmont Irrigation, Inc.) controller, a communication link between the mobile PC and the stationary C:A:M:S had to be established, which

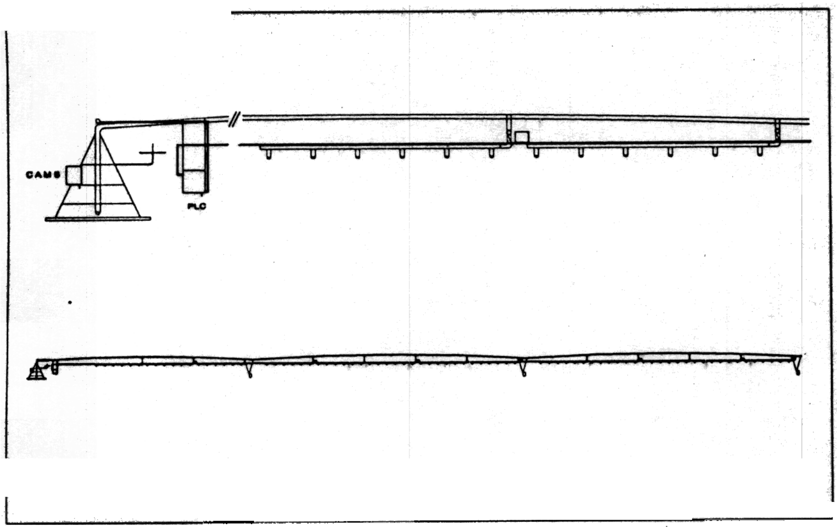

Figure 1. Side view of site-specific center pivot, and close up of tripod and example section.

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[1] Mention of trade names is for information purposes only. No endorsement implied by USDA-ARS or any cooperator of preference over other equipment that may be suitable for the application.

was done with short-range radio-frequency modems (900 MHZ, broad-band modems; Comrad Corp., Indianapolis, IN). The on-board PC repeatedly interrogates the C:A:M:S unit to determine, primarily, the angle of the pivot, but also other parameters to provide assurance the system is functioning properly. From the angle and the segment position on the truss, the position in polar coordinates was fixed. (The angle reported was found to be systematically in error, so a correction was determined with surveying techniques, and built into the software.) When the location has been determined, the program checks whether a boundary has been crossed. If not, the interrogation cycle repeats until something needs to change. When a boundary is crossed, the expected application map is checked, the appropriate table lookup is performed, and the solenoid registers set accordingly.

Injection of nutrients into the irrigation water was accomplished using a 4-head, 24V DC variable-rate pump (Ozawa Precision Metering Pump, model 40320), check valve, and nurse tank connected to the stationary vertical riser at the pivot point. Because the flow rate of water could vary depending on the spatial application schedule, the amount of fertilizer injected into the boom needed to vary proportionately in order to hold the concentration constant. This was done by having the PC on board the PLC calculate the aggregate flow rate, calculate the required injection rate, compute the 0-5V DC voltage setting required to provide that, and report that to the operator. For this season, the operation was monitored and controlled manually using operator inputs to a CR7X (Campbell Scientific Inc., Logan, UT). For later operations, the 0-5 V DC value will be connected directly to the pump. Spatially-variable application of nutrients was done using a minimal, spatially-variable irrigation, but with uniform concentration. Concurrent spatial control of water and nutrients would require distributed control of multiple injection points. Although sophisticated, controlling such a system would not be particularly difficult. The requirement for multiple pumps made this option cost-prohibitive at this time.

Demonstration in a Replicated Field Experiment

The pivot described above was sited on a relatively uniform soil area (USDA-SCS, 1986), chosen specifically for proving the technology under conditions somewhat more controlled than the highly variable long-term spatial yield field. The primary experimental objectives were to test rotation and irrigation effects on a corn-soybean rotation vs continuous corn under conservation tillage. A secondary objective was to test subsoiling against not doing so, in the possible trade-off of irrigation to manage water rather than subsoiling to increase the rooting depth.

There were 144 treatment plots in total: 4 replications x 3 rotations (corn-corn, corn-soybean, soybean-corn) x 2 tillage (subsoiled, non-subsoiled) x 3 water managements (rainfed, tensiometer, crop stress) x 2 nitrogen (single sidedress, incremental appl.). In 1995, the latter two water management treatments were both operated based on tensiometers. The individual plots were laid out in a regular 7.5° by 9.1-m (30-ft) pattern, which made the minimum plot length 10 m in section 7, and 15 m in section 13. As seen in Fig. 2, the four replicates were sited in the outer

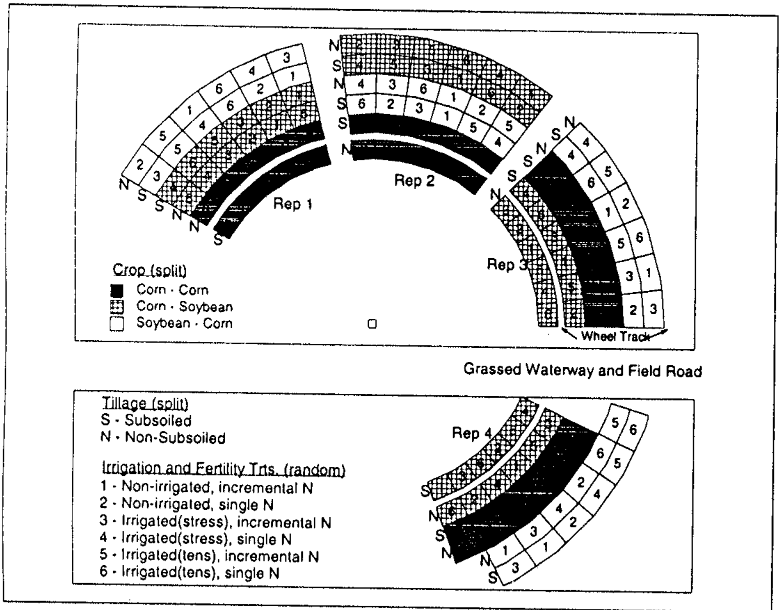

Figure 2. Plot plan for replicated field experiment used to test site-specific center pivot under controlled conditions.

annulus, on the most uniform soil areas. The outer rings were used so that the planting and other operations could be done without sharp turns. All operations were done on the circle rather than with straight rows. This, often done in commercial operations, greatly simplified matters in this experiment.

Table 1 lists fertilization operations during this season. All nitrogen fertilization was accomplished through injection of urea-ammonium-nitrate (UAN 24S) through the system. Included are time, amount of N applied, and amount of irrigation to achieve the fertilization. To prevent spray drift, 1.5" layflat hose was placed around the 2x nozzles and extended to the ground. The 2x nozzles provided 3.6 mm of irrigation at 50% duty cycle and 1.8 mm at 100%.

Table 1. Fertilization via injection through site-specific center pivot.

Date	N Application	Speed, #passes	Irrigation amount	Treatments fertilized
6/1/95	22.5 kg/ha	50%, 1	3.6 mm	All
6/7/95	112.3 kg/ha	100%, 2	3.6 mm	Single
6/8/95	22.5 kg/ha	50%, 1	3.6 mm	Incremental
6/12/95	22.5 kg/ha	50%, 1	3.6 mm	Incremental
6/14/95	22.5 kg/ha	50%, 1	3.6 mm	Incremental
6/19/95	22.5 kg/ha	50%, 1	3.6 mm	Incremental
6/21/95	22.5 kg/ha	50%, 1	3.6 mm	Incremental

Observations from Season's Use

The site-specific center pivot evolved from the basic commercial machine in March, 1995, to a functioning, proven technology by summer's end. Control software was primitive and fragile initially, but similarly evolved through modification and experience such that operation was possible via the remote C:A:M:S unit by the end of the summer. Prior measurements of system uniformity had demonstrated acceptable distribution within control elements as well as expected border effects between elements with contrasting application depths (Omary et al., 1996). Results from the season presented no evidence that uniformity or border width had changed. Surface redistribution had been a concern during design, because of the small wetted radius of the sprinkler, but even the collection into layflat hose for fertilization did not cause excessive local ponding and runoff.

Changes for the Future

The next steps will include outfitting the second pivot with variable rate irrigation and fertilization based on experiences gained with the first pivot, outfitting both with low-volume pesticide variable-rate application equipment, adding sensors to the machines to detect stress, and modifying software to accommodate irregular soil unit boundaries.

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PROCEEDINGS

OF THE

THIRD INTERNATIONAL CONFERENCE ON

PRECISION AGRICULTURE

June 23-26, 1996

Minneapolis, Minnesota

Editors

P.C. Robert, R.H. Rust, and W.E. Larson

Conducted by the
PRECISION AGRICULTURE CENTER
Department of Soil, Water, and Climate
University of Minnesota
St. Paul, Minnesota

Published by
American Society of Agronomy
Crop Science Society of America
Soil Science Society of America

Related Society Publications

Proceedings of the First Workshop Soil-Specific Crop Management. A Workshop on Research and Development Issues. 1993. Robert, P.C., R.H. Rust, and W.E. Larson (ed.) Minneapolis, MN. April 14-16, 1992. ASA, CSSA, SSSA, Madison, WI.

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